VISUAL SEMANTICS EMERGENCE TO SUPPORT CREATIVE DESIGNING: A COMPUTATIONAL VIEW

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Abstract. One computational model of creative designing involves the introduction of new variables or schemas into the designing process. This paper describes and elaborates an approach where an emergence process is used to emerge visual semantics features in a design as it proceeds. In particular visual symmetry, visual rhythm, visual movement and visual balance are emerged. The processes of emergence introduce new variables into the design process. Emergence becomes one of the computational processes capable of playing a role in creative designing.

1. Introduction

Creative design can be viewed from two quite different perspectives. The first deals with creativity as embodied in the design itself. This is a societal process which, more precisely, ascribes some creativity to the resulting design. The second perspective does not deny the first but rather adds that there are some processes of designing which are more likely to lead to creative designs than others (Gero, 1994). We will use the word 'design' to mean the artefact which is being designed and the word 'designing' to mean the process by which designs are produced. It is this second perspective which is developed further here. Whilst there are many processes which can lay claim to being creative designing processes the one we wish to present here is particularly concerned with the notion of schemas, how they can be changed computationally and how this affects the designing process. The process we will be discussing relates to visual emergence.

Emergence is defined as the process of making explicit properties which previously were only implicit. In computational terms emergence is a process which results in properties which previously were not represented being represented explicitly. However, current computer support for designers in CAD systems has critical limitations in the interpretation of drawn shapes to capture even the simplest emergent properties. Graphical emergence such as visual symmetry and visual rhythm which are perceivable by human beings are not possible in current CAD systems. Inadvertently such systems have enforced fixation, ie, only those properties which are explicitly represented are available to be manipulated – no alternatives are possible, so that it is not surprising that these systems are not used in the early stage of designing which is the critical stage of creative designing.

Visual emergence is one of paradigms observed in creative designing (Schön and Wiggins, 1992). It has the capacity to allow designers to look at unexpected or emergent visual structures from what is in front of them. As a consequence, other alternatives for developing the design become possible. The demands for developing computational model of visual emergence are directly related to the demands for using computer systems in creative designing.

This paper describes the ideas behind the development of a computational model of visual semantics emergence as a creative designing process, where creative designing processes introduce new design schemas, variables or properties into the design representation thus providing the opportunity for creative designs to result.

The remainder of this paper introduces the concepts of visual semantics emergence, describes a formal representation for shape semantics, introduces a model of a shape semantics emergence process with its computational analog with examples, before concluding with a discussion of the significance of the endeavour.

2. Visual Semantic Emergence

2.1 INTRODUCTION

Visual semantics emergence is the phenomenon of making explicit meaningful visual patterns, which were not explicitly indicated, by grouping explicit or implicit structures of objects in defined ways. It is a phenomenon experienced by all humans. In particular, this phenomenon has been studied by Gestalt psychologists, who formulated various laws governing figure perception (Palmer, 1983). Some principles contained in these laws of perception can be applied to architectural and graphic art design (Meiss, 1986). Various types of emergent visual semantics can be explained using these laws of perception .

Grouping structures is supported by such factors as: repetition, similarity, proximity, symmetry and orientation. For example, symmetrically located pattern elements tend to be viewed as organizing themselves into groups. Thus, visual symmetry has been regarded as a salient feature of good form by psychologists. Much empirical evidence indicates that symmetry affects the visual perception of form (Locher and Nodine, 1989). The principle of visual symmetry has been extensively used in various visually-oriented design domains, particularly in architectural design. Figure 1 illustrates various types of emergent symmetry found in one figure.

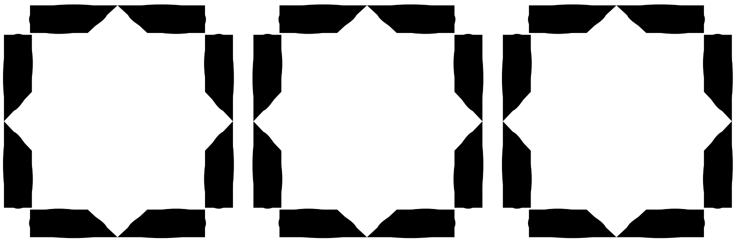


Figure 1: A composition in which various types of emergent symmetry could be observed by a viewer. They include translational symmetry, reflectional symmetry and rotational symmetry. This figure also contains a number of emergent graphical forms which contribute to the emergent symmetry.

Repetition of aligned elements, where all the elements are similar or equivalent, plays an important role in grouping. This grouping could be conceived of as some form of visual semantics such as visual rhythm or visual movement (see Section 2.3 for definitions of these concepts). Figure 2 shows a repetition of aligned elements which produces the beginnings of emergent visual rhythm and emergent visual movement.

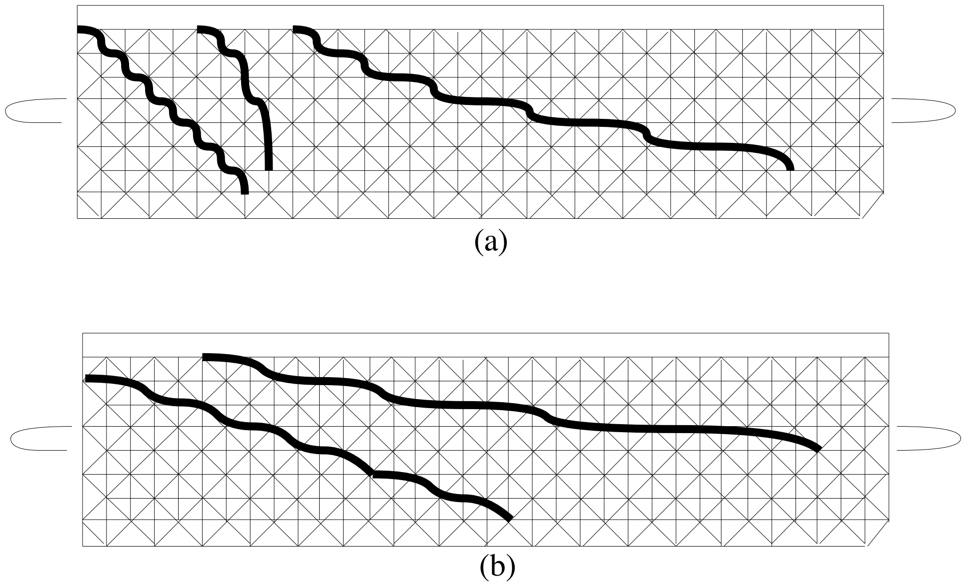


Figure 2 : (a) and (b) Emergence of visual rhythm and visual movement by repetition of aligned equivalent and similar elements in this Filigree Warehouse elevation (Blaser W. (1980). *Filigree Architecture,* Wepf, Basel, p.131).

In a repetitive structure, the intervals or elements may gradually change their form, size or orientation. This factor also supports emergence of visual movement. For example, emergent visual movement is clearly seen in the drawings by August Choisy of the southern temple at Thebes where the movement towards the heart of the sanctuary can be perceived not only in the plan but also in section as shown in Figure 3.

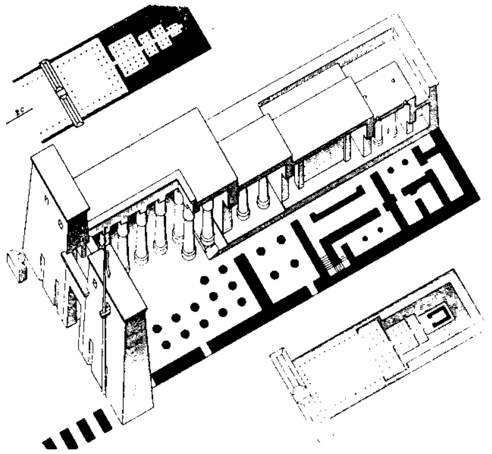
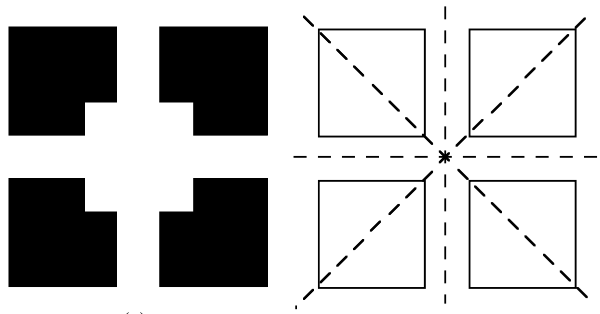


Figure 3 : Visual movement in the southern temple of Thebes (Meiss, P. (1986). *Elements of Architecture*, Van Nostrand Reinhold, London, p.42).

2.2 VISUAL SEMANTIC EMERGENCE IN DESIGN

Visual semantics emergence plays a significant role in introducing new schemas and consequently new variables into a design representation. A schema is a knowledge structure where knowledge is organised in chunks of related concepts. Visual semantics emergence maps directly onto the concept of changing schemas since a schema which was not previously used in the design is generally needed to describe the emergent property. Visual semantics emergence allows designers to refocus their attention and/or reinterpret the results of their activities. In our conception of the creative aspect of designing this reinterpretation of what has been drawn is claimed to play an important role. It provides opportunities for designers to conceptualise what has been drawn differently from what was intended when it was drawn. Moreover, it affects organising decisions by providing a different order and meaning to what was originally intended, and as a consequence plays a role in the generation of the final form in visually-oriented design. Take as an example the four L-shaped polygons shown in Figure 4(a). If the schema is concerned with L-shaped polygons then only those polygons will be found. However, if the schema is concerned with reflectional symmetry then the symmetry axes shown in Figure 4(b) will be found. These could be used by the designer as a fundamental concept in developing the design further. If the schema is concerned with rotational symmetry the original figure now becomes that shown in Figure 4(c).

Drawn shapes play a critical role in various design domains and particularly in architectural design not only in representing a design concept but also in allowing the designer to reinterpret them to develop new ideas. From seeing what was intended to be drawn, intentional and/or unintentional patterns of shapes are identified. The patterns can be grouped into dominant themes or formative ideas which can conceivably be used in the generation of designs. A formative idea is understood to be a concept which a designer can use to influence or give form to a design. In this paper formative ideas from shapes are considered as shape semantics, such as visual symmetry, visual rhythm, visual movement and visual balance.



(a) (b) (c)

Figure 4: (a) Four L-shaped polygons which are explicitly represented; (b) emergent reflectional symmetry, the axes of symmetry are shown as dotted lines and (c) emergent rotational symmetry, the rotations are shown as curved lines.

2.3 DEFINITIONS

We will restrict our interest in visual semantics emergence to the domain of shapes, so called *shape semantics emergence,* although the conceptual approach may well be applicable in other domains. *Shape semantics* is the interpretation of predefined patterns of groups of shapes. A *primary shape semantics* is a visual pattern of relationships of shapes which is represented explicitly and intentionally by designers. An *emergent shape semantics* is a visual pattern of shapes that exists only implicitly in the relationships of shapes, and is never explicitly input and is not represented at input time. Many such patterns of relationships have predefined labels. *Shape semantics emergence* is the process of recognizing emergent shape semantics and primary shape semantics from primary shapes and/or emergent shapes.

Figure 5 shows a quilt design from which examples of primary shapes, primary shape semantics and emergent shape semantics can be determined. The next section describes four classes of shape semantics in a little more detail.

2.4 SHAPE SEMANTICS IN ARCHITECTURAL DESIGN

There is a vast collection of possible architectural shape semantics which could be emerged. However, here, we will deal with only a limited number of shape semantics from architectural design in order to illustrate and demonstrate the ideas involved. Four classes of shape semantics of architectural design are of interest through interpretations of the visual patterns from plans, facades and perspectives: visual symmetry, visual rhythm, visual movement and visual balance.

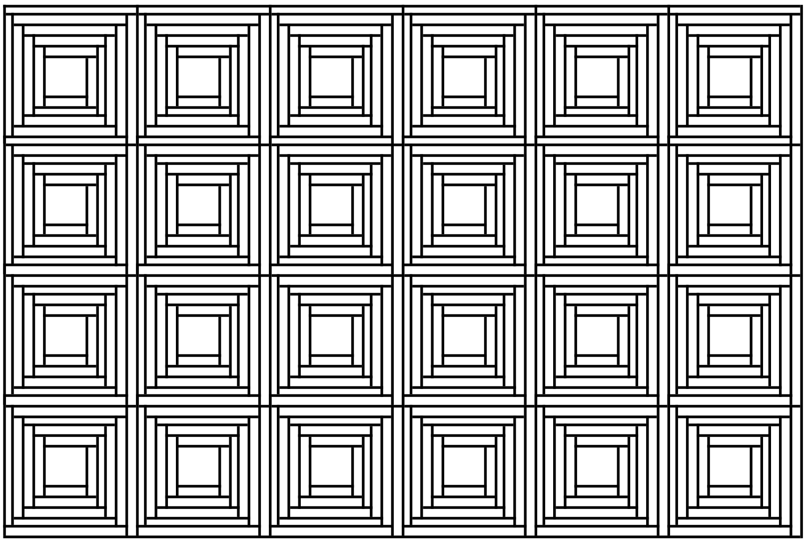


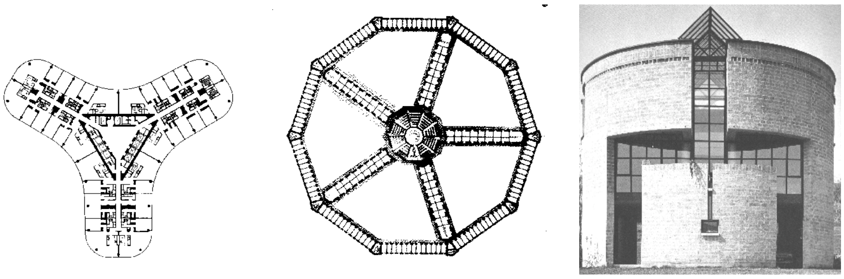
Figure 5: The quilt design from which many visual semantics can be emerged (after Holstein, J. (1973) *Pieced Quilt: An American Design Tradition,* New York Graphic Society, Greenwich, p.[ ])

2.4.1 Visual symmetry

A shape or group of shapes is defined as symmetrical to the extent that it satisfies the symmetry operations of: reflection, rotation or translation. Each type of symmetry can be found in many designs from ancient architecture to modern times. Figure 6(a) shows an example from which reflectional and rotational symmetry can be emerged. There are three different reflectional axes set at 120° to one another. The plan of Bevans' prison can be viewed as being designed by rotating one main wing containing prison cells about the administrative core four times as in Figure 6(b). Figure 6(c) illustrates reflectional symmetry from the facade of a house by Botta.

2.4.2 Visual rhythm

Visual rhythm is a pattern of relationships of equivalent shapes or groups of shapes such that the pattern contains repetition along one or more axes. Many examples of visual rhythm can be emerged from the facade of the Concours for 800 apartments at Strassburg shown in Figure 7.



(a) (b) (c)

Figure 6: Emergence of visual symmetry in architectural plans and facade: (a) reflectional and rotational symmetry: Lake Point Tower (Geoge Schipporeit and John Heinrich, 1965-1968) (from Blaser W. (1980). *Filigree Architecture,* Wepf, Basel, p.198); (b) rotational symmetry: Bevans' model radial prison (Bevans, 1819) (from Markus, T.A. (1993) *Buildings & Power,* Routledge, London and New York, p.139); and (c) reflectional symmetry: Casa Rotonda (Mario Botta, 1980-1981) (from Anon. (1988). *Roots of Modern Architecture*, A.D.A. Edita, Tokyo, p.87).

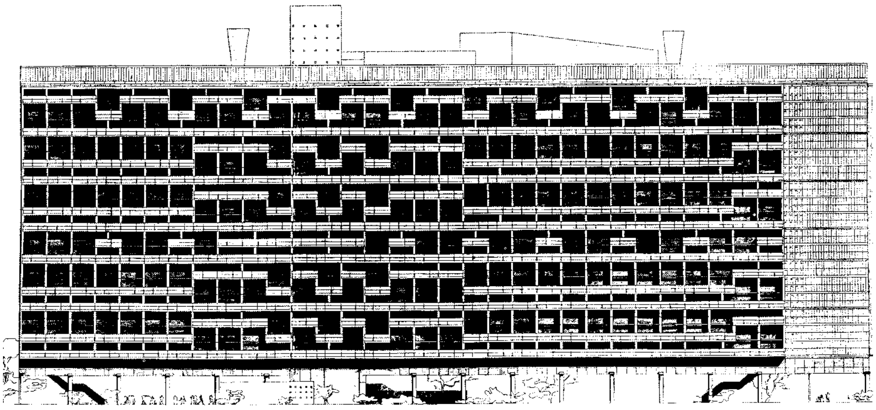
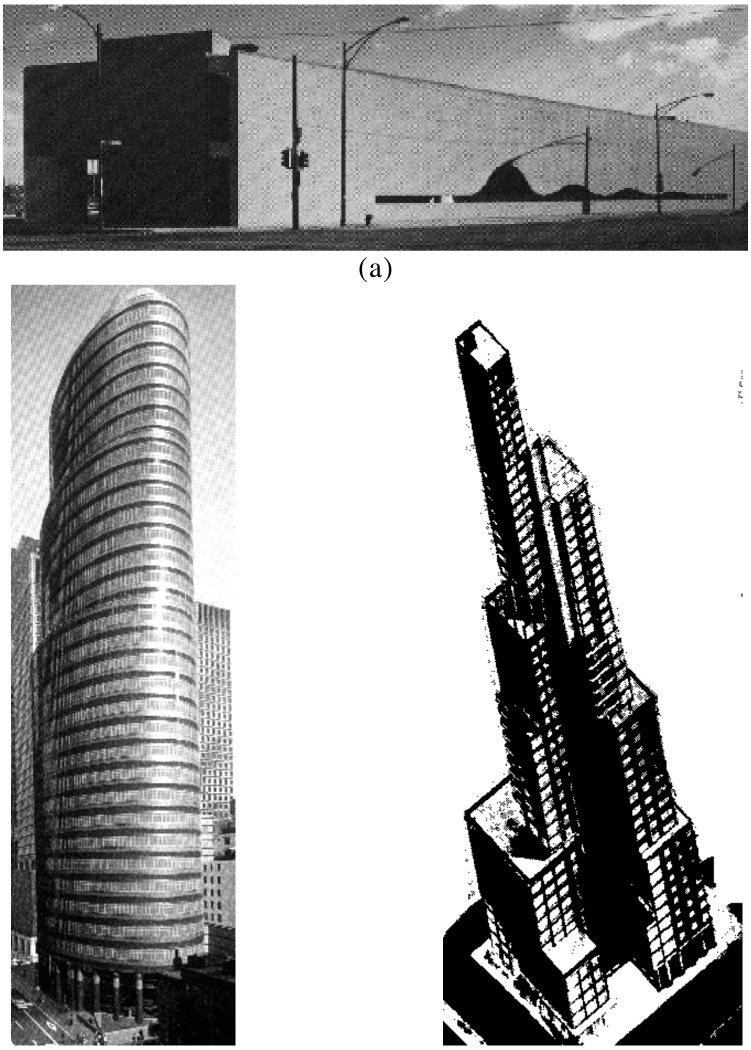


Figure 7: Emergence of visual rhythm from the facade of the Concours for 800 apartments at Strassburg (Le Corbusier, 1951) (from Boesiger, W. and Girsberger, H. (1967), *Le Corbusier 1910-1965,* Thames and Hudson, London, p.134)

2.4.3 Visual movement

Visual movement is a pattern of relationships of equivalent shapes or groups of shapes such that the pattern contains a transformed repetition along one or more axes. Size, interval and orientation are factors related to the perception of visual movement in architectural design. The facade of the Illinios Regional Library for the Blind and Physically Handicapped, Figure 8(a), shows aligned curved shapes which are gradually decreasing in size from left to right. The two buildings in Figures 8(b) and 8(c) contain visual movement in the upward direction, produced by reducing their volumes in that direction.



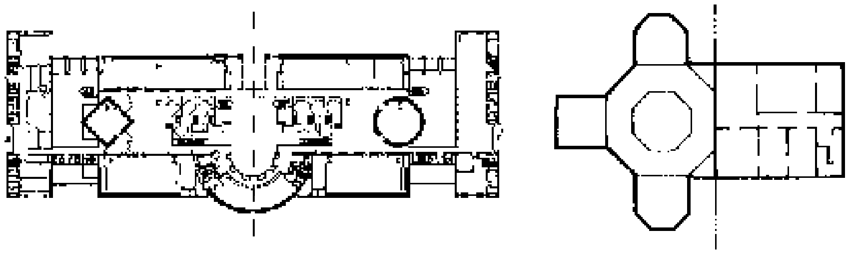
(a)

(b) (c)

Figure 8 : Emergence of visual movement from architectural facade and perspectives: (a) visual movement from the facade of The Illinios Regional Library for the Blind and Physically Handicapped (Stanley Tigeeman) (from Abercrombie, S. (1984) *Architecture as Art: An Esthetic Analysis*, Van Nostrand Reinhold, New York, p.162); (b) 53rd At Third (Philip Johnson, 1983-1985) (from Johnson, P. (1985) *Philip Johnson/John Burgee: Architecture 1979-1985*, Rizzoli, New York, p.135); and (c) exercise model (Lopatin, S., 1923) (from Zygas, K. (1981) *Form Follows Form*, UMI Research Press, Michigan).

2.4.4 Visual balance

Visual balance occurs when a shape or group of shapes is perceptually equivalent on both sides of an axis of balance. Figure 9(a) illustrates visual balance where within the group of shapes two different shapes are used and balance is still maintained. Two completely different geometric shapes in one architectural plan occur in the visual balance shown in Figure 9(b).



(a) (b)

Figure 9: Emergence of visual balance from architectural plans: (a) Yokohama Art Museum (Kenzo Tange, 1983) (from Anonymous (1987), *Kenzo Tange Associates*, Process Architecture, Tokyo): and (b) Observatory in Berlin (Karl Friedrich Schinkel, 1835) (from Clark, R. H. and Pause, M. (1985). *Precedents in Architecture*, Van Nostrand Reinhold, New York, p.176).

3 Shape Semantics Representation

Various types of shape semantics can be represented at the symbolic level. The general representation of shape semantics constructed of shapes is (Gero and Jun, 1994)

$$\boldsymbol{S} = \{N_s;\ \text{constraints}\}$$

where N_s is the number of shapes constituting shape semantics **S** and the constraints, which constrain behaviours or properties resulting from the shapes, based upon which particular shape semantics are defined. A shape is defined as a bounded polyline. A bounded polyline is a polyline, for any point on the boundary of which there exists at least one circuit composed of line segments which start from and end at the point without covering any line segment more than once. Here a shape and an enclosed shape have the same meaning. A shape is represented by infinite maximal lines (Gero and Yan, 1994) as the representation primitive to support shape semantics recognition. Representation of four types of shape semantics are introduced here.

3.1 VISUAL SYMMETRY

When the constraints of shape semantics are isometric transformational constraints, a class of symmetry exists. Therefore the symbolic representation of symmetry from the general expression for shape semantics is (Gero and Jun, 1994)

$$\boldsymbol{S} = \{N_s\ ;\ C_t\}$$

where C_t are isometric transformational constraints.

There are four types of constraints on isometric transformations of interest here: translational constraints (denoted by □), rotational constraints (denoted by □), reflectional constraints (denoted by □), and glide reflectional constraints (denoted by □). Thus, the symbolic representation of symmetry can be extended to

$\boldsymbol{S}$ = { N_s ; □, □, □, □}.

Whenever symmetry is discovered, there is an isometric operator (denoted by □). Therefore the following reasoning is possible

□(S_i) = (S_j) <=> Symmetry exists between S_i and S_j.

Where <=> means logical equivalence.

Isometric transformational constraints concern the structures within which corresponding infinite maximal lines and corresponding intersections are organised. They are represented as groups of corresponding intersections or topological properties of emergent segments consisting of corresponding intersections (Gero and Yan, 1994). Let l_i and l_j be infinite maximal lines and i_{ij} be their intersection. For example, let l_i, l_j, l_k belong to S_i and l_p, l_q, l_r belong to S_j. The representation of two primary triangles is

S_i = {3; [i_{ij}, i_{ik}, i_{jk}]},
S_j = {3; [i_{pq}, i_{pr}, i_{qr}]}.

where a pair of square brackets, "[" and "]", represents an enclosed a circuit of lines segments, i.e. a shape (bounded polyline) (Gero and Yan, 1994).

Transformational relationships are implied when □(S_i) = (S_j) exists, ie,
□(S_i) = (S_j) => □(one of ls □ S_i) = (one of ls □ S_j),
□(S_i) = (S_j) => □(one of is □ S_i) = (one of is □ S_j).

As a result, the following corresponding infinite maximal lines and corresponding intersections are inferred when □(S_i) = (S_j).

Corresponding infinite maximal lines:
l_i□ l_p, l_j□ l_q, l_k□ l_r,.

Corresponding intersections:
i_{ij}□ i_{pq}, i_{ik}□ i_{pr}, i_{jk}□ i_{qr}.

Where A□ B means A corresponds to B.

Emergent segments are inferred from corresponding segments. In this example three emergent segments are inferred as follows:
i_{ij}□ i_{pq} => (i_{ij}, i_{pq}),
i_{ik}□ i_{pr} => (i_{ik}, i_{pr}),
i_{jk}□ i_{qr} => (i_{jk}, i_{qr}).

1. Translational constraint (□)

Translational symmetry exists when a group of two emergent segments which are decomposed into four corresponding intersections forms part of a parallelogram. The other two sides of the parallelogram must be the corresponding sides from each of the two primary shapes (Baglivo and Graver, 1983) as shown in Figure 10.

(i_{ij}, i_{pq}) □ (i_{ik}, i_{pr}) => {4 ; [$i_{ij}, i_{pq}, i_{ik}, i_{pr}$] ; $l_i // l_p$, $(i_{ij}, i_{pq}) // (i_{ik}, i_{pr})$}.
(i_{ij}, i_{pq}) □ (i_{jk}, i_{qr}) => {4 ; [$i_{ij}, i_{pq}, i_{jk}, i_{qr}$] ; $l_j // l_q$, $(i_{ij}, i_{pq}) // (i_{jk}, i_{qr})$}.
(i_{ik}, i_{pr}) □ (i_{jk}, i_{qr}) => {4 ; [$i_{ik}, i_{pr}, i_{jk}, i_{qr}$] ; $l_k // l_r$, $(i_{ik}, i_{pr}) // (i_{jk}, i_{qr})$}.

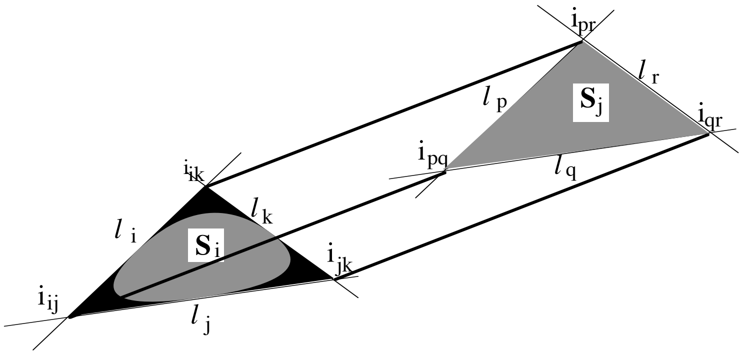


Figure 10: Translational symmetry constraint represented graphically

2. Reflectional constraint (□)

Reflectional symmetry exists when a group of two emergent segments which are decomposed into four corresponding intersections forms the parallel pair of lines of a trapezoid. The other two sides of the trapezoid must be the corresponding sides from each of the two primary shapes and the midpoints of emergent segments are collinear (Jenkins, 1983). In addition, perpendicular bisectors of all emergent segments are coincident (March and Steadman, 1974; Baglivo and Graver, 1983). Figure 11 illustrates the constraints for reflectional symmetry.

(i_{ij}, i_{pq}) □ (i_{ik}, i_{pr}) => {4 ; [$i_{ij}, i_{pq}, i_{ik}, i_{pr}$] ; $(i_{ij}, i_{pq}) // (i_{ik}, i_{pr})$}.
(i_{ij}, i_{pq}) □ (i_{jk}, i_{qr}) => {4 ; [$i_{ij}, i_{pq}, i_{jk}, i_{qr}$] ; $(i_{ij}, i_{pq}) // (i_{jk}, i_{qr})$}.
(i_{ik}, i_{pr}) □ (i_{jk}, i_{qr}) => {4 ; [$i_{ik}, i_{pr}, i_{jk}, i_{qr}$] ; $(i_{ik}, i_{pr}) // (i_{jk}, i_{qr})$}.

In addition, the midpoints of emergent segments, $i_{(i_{jk},\, i_{qr})\mathbf{M}}$, are inferred by following inference.

$i_{(i_{jk},\, i_{qr})k}$ □ (i_{jk}, i_{qr}) □ $d(i_{jk}, i_{(i_{jk},\, i_{qr})k}) = d(i_{(i_{jk},\, i_{qr})k}, i_{qr})$
=> $i_{(i_{jk},\, i_{qr})k}$ becomes $i_{(i_{jk},\, i_{qr})\mathbf{M}}$,
where $i_{(i_{jk},\, i_{qr})k}$ denotes any point within a line segment, (i_{jk}, i_{qr}).

The following emergent segments are inferred.

$i_{(i_{ij},\, i_{pq})k}$ □ (i_{ij}, i_{pq}) □ $d(i_{ij}, i_{(i_{ij},\, i_{pq})k}) = d(i_{pq}, i_{(i_{ij},\, i_{pq})k})$
=> □ $i_{(i_{ij},\, i_{pq})\mathbf{M}}$.
$i_{(i_{ik},\, i_{pr})k}$ □ (i_{ik}, i_{pr}) □ $d(i_{ik}, i_{(i_{ik},\, i_{pr})k}) = d(i_{pr}, i_{(i_{ik},\, i_{pr})k})$
=> □ $i_{(i_{ik},\, i_{pr})\mathbf{M}}$.
$i_{(i_{jk},\, i_{qr})k}$ □ (i_{jk}, i_{qr}) □ $d(i_{jk}, i_{(i_{jk},\, i_{qr})k}) = d(i_{(i_{jk},\, i_{qr})k}, i_{qr})$
=> □ $i_{(i_{jk},\, i_{qr})\mathbf{M}}$,

The midpoints of emergent segments are collinear.

$i_{(i_{ij},\, i_{pq})\mathbf{M}}$, $i_{(i_{ik},\, i_{pr})\mathbf{M}}$ and $i_{(i_{jk},\, i_{qr})\mathbf{M}}$ lie on a unique l_m.

Perpendicular bisectors of all emergent segments are inferred.

□ $i_{(i_{ij},\, i_{pq})\mathbf{M}}$ □ (i_{ij}, i_{pq}) □ l_m => □ $l_{\mathbf{M}}^{i_{(i_{ij},\, \square_{pq})}}$.
□ $i_{(i_{ik},\, i_{pr})\mathbf{M}}$ □ (i_{ik}, i_{pr}) □ l_m => □ $l_{\mathbf{M}}^{i_{(i_{ik},\, \square_{pr})}}$.
□ $i_{(i_{jk},\, i_{qr})\mathbf{M}}$ □ (i_{jk}, i_{qr}) □ l_m => □ $l_{\mathbf{M}}^{i_{(i_{jk},\, \square_{qr})}}$.

The perpendicular bisectors of all emergent segments are coincident.

Let $l_{\mathbf{M}}^{i_{(i_{ij},\, \square_{pq})}}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{M}}^{i_{(i_{ik},\, \square_{pr})}}$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{i_{(i_{jk},\, \square_{qr})}}$ be $l_{\mathbf{M}_3}$.
$l_{\mathbf{M}_1}$, $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}_3}$ are coincident => □ $l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$.

In this case, $l_m = l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$. The axis of reflection, L, is regarded as the perpendicular bisectors of all emergent segments. Figure 11 shows the axis of reflectional symmetry.

L (reflectional axis) = $l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$.

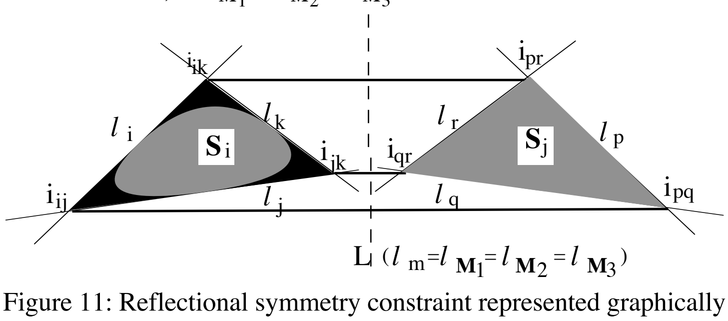


Figure 11: Reflectional symmetry constraint represented graphically

3. Rotational constraint (□)

Rotational symmetry exists when perpendicular bisectors of all emergent segments are concurrent (March and Steadman, 1974; Baglivo and Graver, 1983), as shown in Figure 12.

Let $l_{\mathbf{M}}^{i_{(i_{ij},\,\square_{pq})}}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{M}}^{i_{(i_{ik},\,\square_{pr})}}$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{i_{(i_{jk},\,\square_{qr})}}$ be $l_{\mathbf{M}_3}$.
$l_{\mathbf{M}_1}$, $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}_3}$ are concurrent => $\square\, i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$.

The concurrent point, $i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$. is the centre of rotation.

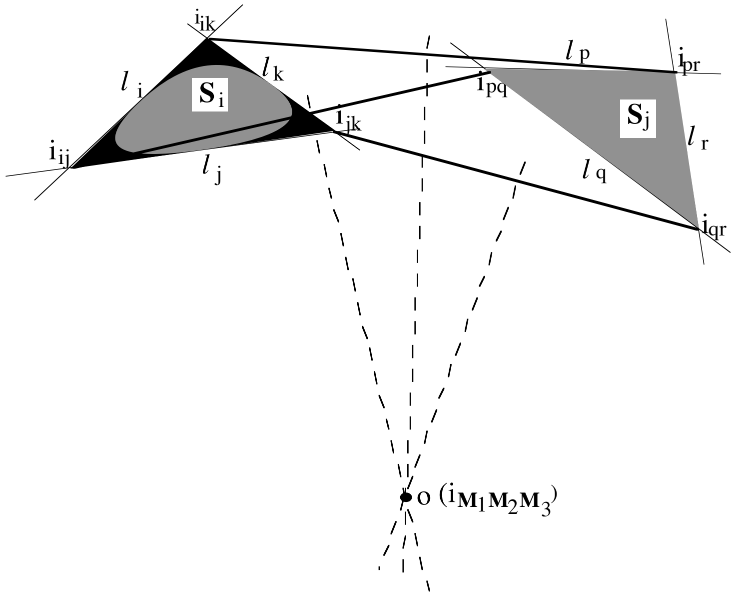


Figure 12: Rotational symmetry constraint represented graphically

4. Glide reflectional constraint (□)
Glide reflectional symmetry exists when the midpoints of emergent segments connecting corresponding intersections in the two primary shapes are collinear (March and Steadman, 1974; Baglivo and Graver, 1983) as shown in Figure 13

$i_{(i_{ij},\, i_{pq})\mathbf{M}}$, $i_{(i_{ik},\, i_{pr})\mathbf{M}}$ and $i_{(i_{jk},\, i_{qr})\mathbf{M}}$ are lying in a certain l_{m}.

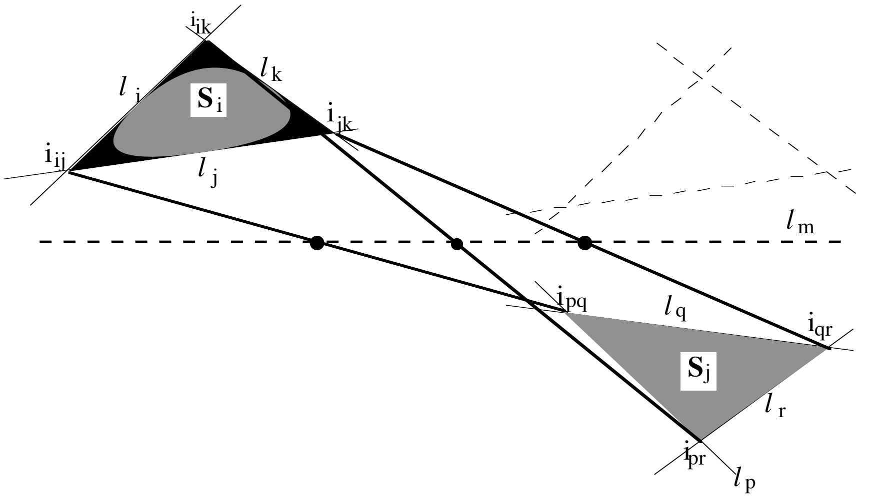


Figure 13: Glide reflectional symmetry constraint represented graphically

3.2 VISUAL RHYTHM

Visual rhythm is defined as the perception of a pattern of relationships of equivalent objects or groups of objects such that the pattern contains repetition along one or more axes. An object may be a single line segment, a shape or a group of line segments. Therefore, the emergence of visual rhythm may be discovered when such repetitions of visual patterns of objects exist.

Objects are treated as units of visual rhythm. When the units are grouped into identical patterns, the pattern is regarded as the unit in visual rhythm. The group, G, is represented by the number of objects (n) and constraints on units.

$$G = n(\text{constraints on units}).$$

Therefore, the representation of visual rhythm becomes a special case of the general equation for shape semantics, ie

$$\boldsymbol{R} = N_g\,(C_r)$$

where $\boldsymbol{R}$ denotes visual rhythm, N_g is the number of groups which produce the repeating patterns and C_r is the rhythm constraints on groups. For generality a group may contain a single line segment, a single enclosed shape, a group of line segments or a group of enclosed shapes.

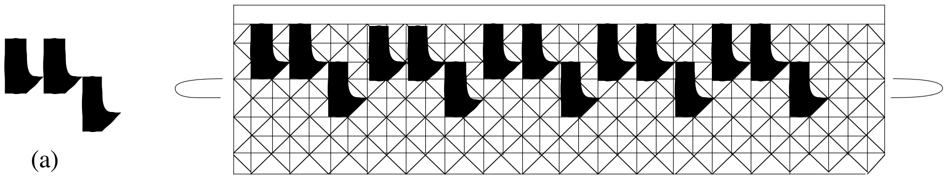
Eight symbols, ←, →, ↑, ↓, ↖, ↗, ↙ and ↘, are using to represent topological constraints on objects in visual rhythm (Gero and Jun, 1995). These describe the following topological constraints on objects.

O_2 is right of O_1 and □(O_2) = O_1 => O_1 ← O_2.

O_1 is left of O_2 and $\square(O_1) = O_2$ => $O_1 \rightarrow O_2$.
O_1 is below O_2 and $\square(O_1) = O_2$ => $O_1 \uparrow O_2$.
O_1 is above O_2 and $\square(O_1) = O_2$ => $O_1 \downarrow O_2$.
O_2 is below right of O_1 and $\square(O_2) = O_1$ => $O_1 \nwarrow O_2$.
O_1 is below left of O_2 and $\square(O_1) = O_2$ => $O_1 \nearrow O_2$.
O_2 is above right of O_1 and $\square(O_2) = O_1$ => $O_1 \swarrow O_2$.
O_1 is above left of O_2 and $\square(O_1) = O_2$ => $O_1 \searrow O_2$.
Where O_i denotes objects and $\square(O_i) = O_j$ means O_i is translated into O_j.

For example, $\boldsymbol{R} = N_g\{G(\rightarrow)\}$ represents N_g identical groups translated from left to right. When a group is a group of enclosed shapes, the same symbols are used for topological constraints on shapes. Figure 14 shows a visual rhythm represented by $\boldsymbol{R} = 5\{G(\rightarrow)\}$. Representation of the group as shown in Figure 14 (a) is defined as follows:

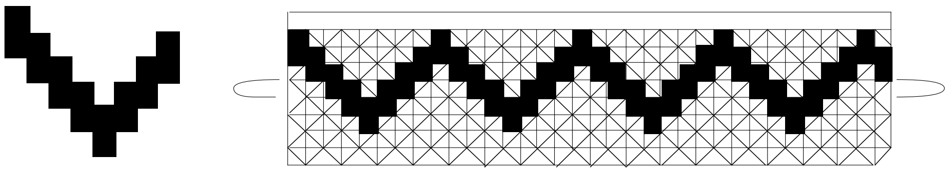
$G = (\rightarrow, \searrow)$
=> $S_1 \rightarrow S_2 \searrow S_3$
=> $\square_1(S_1) = S_2$ and S_1 is left of S_2 $\square$ $\square_2(S_2) = S_3$ and S_2 is above left of S_3.



(a) (b)

Figure 14: Visual rhythm discovered in a facade (a) grouping of units, and (b) the discovered visual rhythm.

Furthermore, consider the group of units shown in Figure 15(a), where $G = (4\searrow, 3\nearrow)$, this results in the visual rhythm represented by $\boldsymbol{R} = 4\{G(\rightarrow)\}$, as shown in Figure 15(b). The last object of the first constraint, $4\searrow$, is the first object of the second constraint, $3\nearrow$.



(a) (b)

Figure 15: Visual rhythm discovered in a facade (a) grouping of units, and (b) the resulting visual rhythm.

Visual rhythm is related to visual symmetry in that it is concerned with identical shapes. Therefore visual symmetry is also discovered as a result.

3.3 VISUAL MOVEMENT

Visual movement is discovered when a pattern of relationships of equivalent objects or object groups contains a transformed repetition aligned with one or more axes in regular or changing intervals. The axis or axes are regarded as the paths of the visual movement. Constraints on axis alignment and intervals between groups are major determinants of the existence of visual movement. Therefore the symbolic representation of visual movement from equation (1) is

$$\boldsymbol{M} = \{N_g;\ \mathrm{C_a}, \mathrm{C_i}\}.$$

where $\boldsymbol{M}$ denotes visual movement, N_g is the number of equivalent or transformed objects or groups of objects, $\mathrm{C_a}$ is the constraints on alignment, and $\mathrm{C_i}$ the constraints on intervals.

Alignment of equivalent object groups exists when corresponding features such as corresponding intersections are aligned. Intervals in aligned equivalent object groups are represented by dimensional constraints on corresponding features. Two types of dimensional constraints for representing intervals are considered: uniform and progressive dimensional constraints. Uniform dimensional constraints require that the dimensions between equivalent features remain constant, whilst progressive dimensional constraints require that the dimensions between equivalent features vary in a defined progression. The symbolic representation of visual movement in equivalent objects is

$$\boldsymbol{M_e} = \{N_g;\ {}_{n}\square_{(+\text{ or }\square)}(\mathrm{G_i}) = \mathrm{G_j}\ \}$$

where $\boldsymbol{M_e}$ denotes visual movement of equivalent object groups, ${}_{n}\square_{+}$ and ${}_{n}\square_{\square}$ represent increasing and decreasing intervals in n numbers of G respectively and $\square(\mathrm{G_i}) = \mathrm{G_j}$ represents translational constraints between $\mathrm{G_i}$ and $\mathrm{G_j}$. Visual movement in Figure 16, for example, is represented as follows, where G is replaced by S since there is only a single shape in a group:

$$\boldsymbol{M_e} = \{9;\ {}_{5}\square_{1+}\ (\mathrm{S_i}) = \mathrm{S_j}\ ,\ {}_{5}\square_{2+}\ (\mathrm{S_i}) = \mathrm{S_j}\},$$

S = .

The last shape in first constraint is the first shape in second constraint in this example.

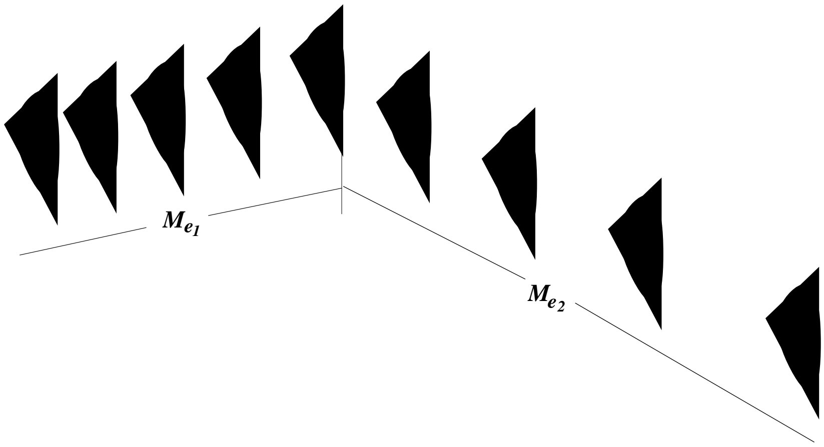


Figure 16: Visual movement from aligned equivalent shapes composed of two different patterns of visual movement

Another type of visual movement can be discovered from aligned transformed object groups. The symbolic representation of visual movement in transformed object groups is

$$\boldsymbol{M_t} = \{N_g;\ {}_{n}\square_{(i+ \text{ or } i\square) \text{ or } (s+ \text{ or } s\square)}\ (G_i) = G_j\}$$

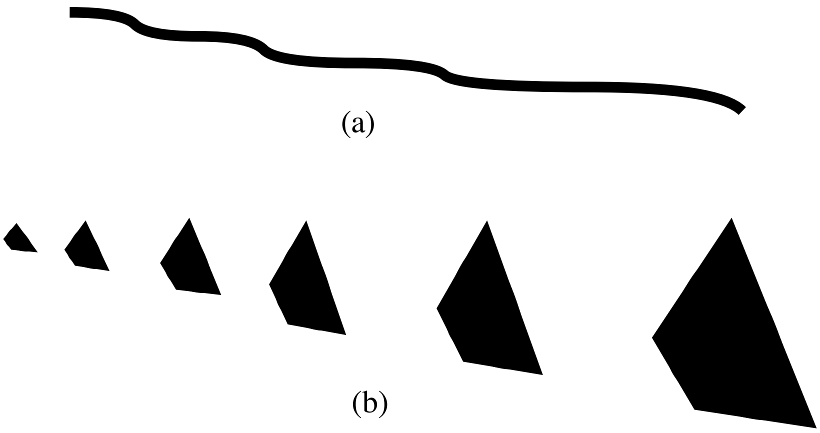
where $\boldsymbol{M_t}$ denotes visual movement of transformed object groups, ${}_{n}\square_{i+}$ and ${}_{n}\square_{i\square}$ represent increasing and decreasing intervals in n numbers of G respectively, ${}_{n}\square_{s+}$ and ${}_{n}\square_{s\square}$ represent increasing and decreasing scales in n numbers of G respectively and $\square(G_i) = G_j$ represents G_i is transformed into G_j with any appropriate transformation. Visual movement in Figure 17, for example, is represented as follows:

Figure 17(a):

$\boldsymbol{M_t} = \{4;\ {}_{4}\square_{s+}(G_i) = G_j\}$,
$\square_{s+}$ is a horizontal scaling operator on G.
G = ;

Figure 17(b):

$\boldsymbol{M_t} = \{6;\ {}_{6}\square_{s+}\ [{}_{6}\square_{i+}(G_i) = G_j]\}$,
$\square_{s+}$ is a scaling operator on G,
$\square_{i+}$ is an operator which increments the distance between shape groups,
G = .



(a)

(b)

Figure 17: Visual movement from aligned transformed shapes

3.4 Visual balance

Visual balance is recognised when an object or group of objects is perceptually equivalent on either side of an axis of balance. Discovering an axis of visual balance plays a crucial role in the discovery of visual balance. There is a geometrical axis of visual balance and semantic axis of visual. The geometrical axis is represented by a constraint on the sizes of objects on either side of the axis and by a constraint on thedistance of the objects to the axis. On the other hand, a semantic axis exists only when there is a semantic feature which maps directly onto the geometric axis or is close to it. Therefore the symbolic representation of visual balance, ***B***, from th general expressionfor shape semantics is

$$\boldsymbol{B} = \{N_s;\ \mathrm{C_b}\}$$

where N_s is the number of objects and $\mathrm{C_b}$ are constraints on axis of balance.

4. Computational Process Model of Shape Semantics Emergence

Figure 18 shows a computational process model of shape semantics emergence. Corresponding structures of objects are inferred by constraints on structures of objects resulting from behaviours of infinite maximal lines. As a result of the process of object correspondence, corresponding infinite maximal lines and intersections are found. After searching infinite maximal lines and intersections, corresponding structures are grouped by a grouping process. If groups satisfy constraints on various types of shape semantics, then these shape semantics are emerged. Thus, a process model of shape semantics emergence involves three steps: (1) searching for corresponding structures of objects – object correspondence; (2) searching for groups from corresponding structures – grouping; and (3) discovering various types of emergent shape semantics.

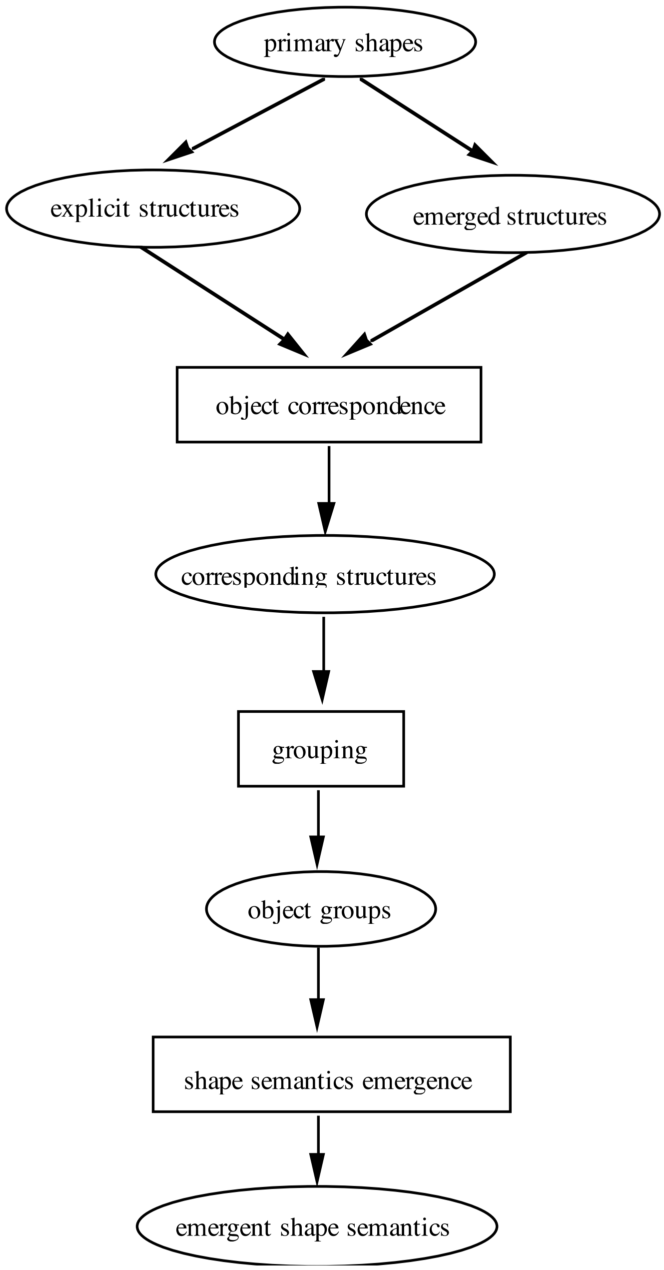


Figure 18: A computational process model of shape semantics emergence

4.1 OBJECT CORRESPONDENCE

Object correspondence involves two distinct steps: (i) finding congruent objects – congruent object correspondence (Gero and Jun, 1994) and (ii) finding transformed objects in terms of size or dimensional constraints – transformed object correspondence as shown in Figure 19. Congruent object correspondence is satisfied when the number of infinite maximal lines, the number of intersections, geometrical properties of infinite maximal lines and dimensional constraints on segments on each infinite maximal line are equivalent between shapes. On the other hand, transformed object correspondence is satisfied when the number of infinite maximal lines, the number of intersections and geometrical properties of infinite maximal lines are equivalent between shapes and there is a constant ratio over the dimensional constraints on segments of each corresponding infinite maximal line.

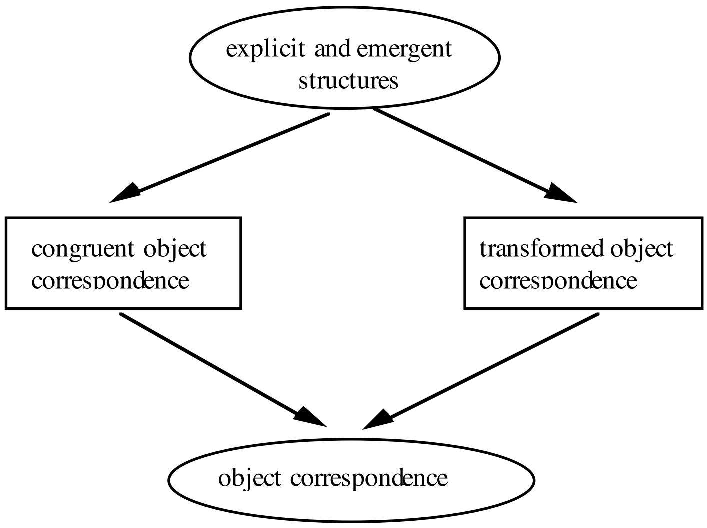


Figure 19: Process of object correspondence

For example, let l_a, l_b, l_c, l_d belong to S_1 and l_p, l_q, l_r, l_s belong to S_2. The representation of two primary four-sided shapes is

$S_1 = \{4; [i_{ab}, i_{bc}, i_{cd}, i_{ad}]\}$
$S_2 = \{4; [i_{pq}, i_{qr}, i_{rs}, i_{ps}]\}$.

After shape hiding (Gero and Yan, 1994) emergent structures can be made explicit, so the representation of this example now becomes
$S_1=\{4; (i_{bd}, i_{ab}, i_{bc}, i_{cd}, i_{ac}, i_{ad})\}$
$S_2=\{4; (i_{qs}, i_{pq}, i_{pr}, i_{qr}, i_{rs}, i_{ps})\}$
where a pair of parenthesis, "(" and ")", represents an ordinary group, in which any two intersections in the group represents a line segment (Gero and Yan, 1994).

Corresponding infinite maximal lines from this representation are found by the following rule:

let the number of infinite maximal lines in two shapes, S_1 and S_2, be N_{l_1} and N_{l_2}, the number of intersections be n_{i_1} and n_{i_2} and number of segments in each infinite maximal line be n_{s_1} and n_{s_2},

R1: $N_{l_1} = N_{l_2}$ □ $n_{i_1} = n_{i_2}$ □ $n_{s_1} = n_{s_2}$
□ □$d(i_{ab}, i_{ad})$ = □$d(i_{pq}, i_{ps})$
=> l_a □ l_p
where □$d(i_{ab}, i_{ad})$ means all dimensional constraints in l_a.

Rule 1, **R1**, is used for finding corresponding infinite maximal lines in corresponding congruent shapes.

R2: $N_{l_1} = N_{l_2}$ □ $n_{i_1} = n_{i_2}$ □ $n_{s_1} = n_{s_2}$
□ k= (□$d(i_{ab}, i_{ad})$ / □$d(i_{pq}, i_{ps})$)
=> l_a □ l_p
where k= (□$d(i_{ab}, i_{ad})$ / □$d(i_{pq}, i_{ps})$) means all dimensional constraints in l_a.and l_p are in the ratio, k.

Rule 2, **R2**, is used for finding corresponding infinite maximal lines in corresponding transformed shapes .

Corresponding infinite maximal lines are inferred through the above process. Finally, corresponding intersections are found by applying the following rule.

R3: l_a □ l_p □ l_b □ l_q □ l_a □ l_b □ l_p □ l_q => i_{ab} □ i_{pq}.

Thus, corresponding infinite maximal lines and intersections are found by **R1** or **R2** and **R3**:

l_a □ l_p, l_b □ l_q, l_c □ l_r, l_d □ l_s, and
i_{ab} □ i_{pq}, i_{ac} □ i_{pr}, i_{ad} □ i_{ps}, i_{bc} □ i_{qr}, i_{bd} □ i_{qs}, i_{cd} □ i_{rs}.

4.2 GROUPING

Corresponding structures require to be grouped. Various types of groups of line segments, enclosed shapes and groups of enclosed shapes result from grouping corresponding intersections. Grouping adjacent intersections may form enclosed shapes otherwise only line segment or groups of line segments are formed. For example, grouping the intersections i_{ab}, i_{bd}, i_{ad} forms a triangle because l_a, l_b and l_d exist and intersect each other, ie:

$\mathbf{G}$ $(i_{ab}, i_{bd}, i_{ad}) \Rightarrow S = \{3; [i_{ab}, i_{bd}, i_{ad}]\}$
where **G** denotes grouping operator.

On the other hand, grouping i_{ab}, i_{ac}, i_{cd} does not form an enclosed shape but a group of line segments because there is no closure:

$\mathbf{G}$ $(i_{ab}, i_{ac}, i_{cd}) \Rightarrow L_g = \{3; (i_{ab}, i_{ac}, i_{cd})\}$
where L_g denotes groups of line segments.

Corresponding enclosed shapes and line segments are found by grouping corresponding intersections in this process.

4.3 SHAPE SEMANTICS EMERGENCE

The process of shape semantics emergence based on symmetries is illustrated in Figure 20. Various types of symmetries are discovered by applying rules from congruent shape groups. In particular, translational symmetry is used in the discovery of visual rhythm and visual movement. If increasing and/or decreasing intervals in translational symmetry exist, visual movement ($\boldsymbol{M_e}$) exists as well. Visual movement ($\boldsymbol{M_t}$) from transformed shape groups is discovered when constraints on intervals between shapes are satisfied.

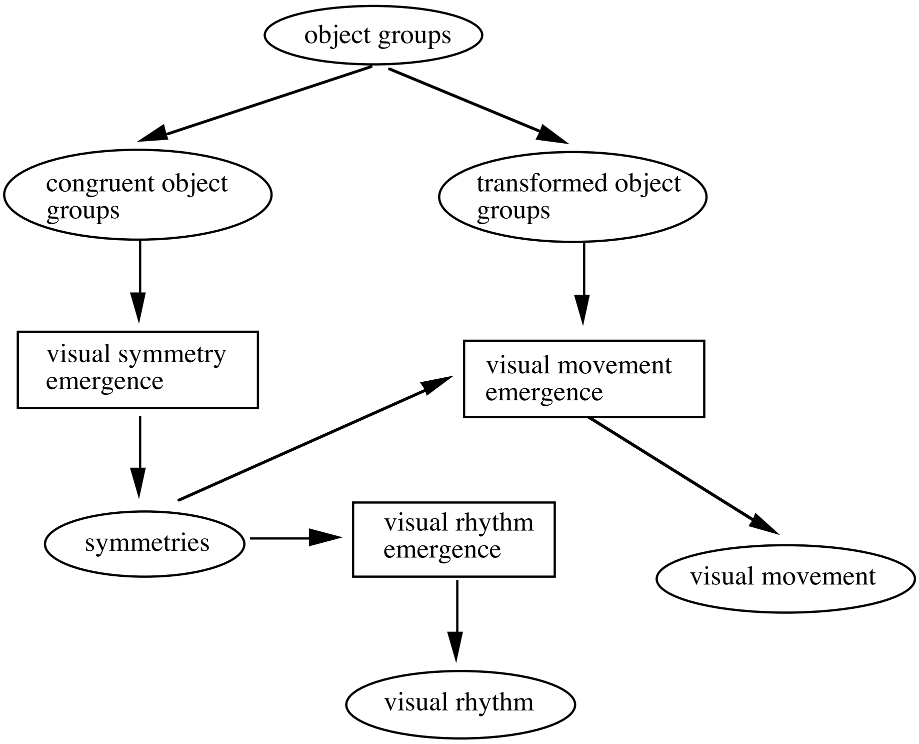


Figure 20: Process of shape semantics emergence based on symmetries

Different types of visual symmetries are discovered by applying rules to congruent groups, in which all structures are found by congruent object correspondence and are grouped. Here again are the corresponding infinite maximal lines and intersections from the continuing example in Section 4.1:

l_a □ l_p, l_b □ l_q, l_c □ l_r, l_d □ l_s, and
i_{ab} □ i_{pq}, i_{ac} □ i_{pr}, i_{ad} □ i_{ps}, i_{bc} □ i_{qr}, i_{bd} □ i_{qs}, i_{cd} □ i_{rs}.

Two corresponding shapes are discovered by grouping corresponding intersections:

G1 $(i_{ab}, i_{ac}, i_{bc}) \Rightarrow S_1 = \{3; [i_{ab}, i_{ac}, i_{bc}]\}$
G2 $(i_{pq}, i_{pr}, i_{qr}) \Rightarrow S_2 = \{3; [i_{pq}, i_{pr}, i_{qr}]\}$.

Symmetries are discovered if one of following rules is satisfied:

R4: $(i_{ab}, i_{pq}) \,//\, (i_{ac}, i_{pr}) \,//\, (i_{bc}, i_{qr})$ □ $l_a // l_p,\ l_b // l_q,\ l_c // l_r$
= >
(i_{ab}, i_{pq}) □ $(i_{ac}, i_{pr}) \Rightarrow \{4 ; [i_{ab}, i_{pq}, i_{ac}, i_{pr}] ; l_a // l_p, (i_{ab}, i_{pq}) // (i_{ac}, i_{pr})\}$.
(i_{ab}, i_{pq}) □ $(i_{bc}, i_{qr}) \Rightarrow \{4 ; [i_{ab}, i_{pq}, i_{bc}, i_{qr}] ; l_b // l_q, (i_{ab}, i_{pq}) // (i_{bc}, i_{qr})\}$.
(i_{ac}, i_{pr}) □ $(i_{bc}, i_{qr}) \Rightarrow \{4 ; [i_{ac}, i_{pr}, i_{bc}, i_{qr}] ; l_c // l_r, (i_{ac}, i_{pr}) // (i_{bc}, i_{qr})\}$.

=> $\mathbf{S}\square$(translational symmetry).

R5: $(i_{ab}, i_{pq}) // (i_{ac}, i_{pr}) // (i_{bc}, i_{qr})$
= >
$(i_{ab}, i_{pq}) \square (i_{ac}, i_{pr})$ => $\{4 ; [i_{ab}, i_{pq}, i_{ac}, i_{pr}] ; (i_{ab}, i_{pq}) // (i_{ac}, i_{pr})\}$.
$(i_{ab}, i_{pq}) \square (i_{bc}, i_{qr})$ => $\{4 ; [i_{ab}, i_{pq}, i_{bc}, i_{qr}] ; (i_{ab}, i_{pq}) // (i_{bc}, i_{qr})\}$.
$(i_{ac}, i_{pr}) \square (i_{bc}, i_{qr})$ => $\{4 ; [i_{ac}, i_{pr}, i_{bc}, i_{qr}] ; (i_{ac}, i_{pr}) // (i_{bc}, i_{qr})\}$.
$\square$ $i_{(i_{ab}, i_{pq})\mathbf{M}}$, $i_{(i_{ac}, i_{pr})\mathbf{M}}$, and $i_{(i_{bc}, i_{qr})\mathbf{M}}$ are lying in a certain l_m,
$\square$ $l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$,
(Let $l_{\mathbf{M}}^{(i_{ab}, \square_{pq})}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{M}}^{(i_{ac}, \square_{pr})}$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{(i_{bc}, \square_{qr})}$ be $l_{\mathbf{M}_3}$)
=> $\mathbf{S}\square$ (reflectional symmetry).
(L (reflectional axis) = $l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$).

R6: $\square\, i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$,
(Let $l_{\mathbf{M}}^{(i_{ab}, \square_{pq})}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{M}}^{(i_{ac}, \square_{pr})}$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{(i_{bc}, \square_{qr})}$ be $l_{\mathbf{M}_3}$)
=> $\mathbf{S}\square$ (rotational symmetry).
(rotational point is $i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$).

R7: $i_{(i_{ab}, i_{pq})\mathbf{M}}$, $i_{(i_{ac}, i_{pr})\mathbf{M}}$, and $i_{(i_{bc}, i_{qr})\mathbf{M}}$ are lying in a certain l_m,
=> $\mathbf{S}\square$(glide reflectional symmetry).

Visual rhythms are discovered as repetitions of identical groups of objects. They are found when equivalent translational constraints exist over identical groups. A visual rhythm is discovered, for example, when the following rule is satisfied.

Let the corresponding objects (could be line segments or shapes) be:

$O_1 \square O_5, O_2 \square O_6, O_3 \square O_7, O_4 \square O_8$.

R8: $O_1 \square O_5, O_2 \square O_6, O_3 \square O_7, O_4 \square O_8$
$\square\ \square_1(O_1) = O_2, \square_2(O_2) = O_3, \square_3(O_3) = O_4$
=> $G_1 = \{O_1, O_2, O_3, O_4\} \square G_2 = \{O_5, O_6, O_7, O_8\}$
=> $\square(G_1) = G_2$
=> $\square\boldsymbol{R}$

Visual movement is found when identical groups are translated along an axis but with changing intervals or with transformed repeating groups. Therefore, visual movement is discovered when the following rule is satisfied.

Let congruent object groups be:

G_1, G_2, G_3, G_4, G_5.

First, visual movement from congruent objects, $\boldsymbol{M_e}$, is discovered by satisfying the following rule:

R9: $\square_1(G_1) = G_2, \square_2(G_2) = G_3, \square_3(G_3) = G_4, \square_4(G_4) = G_5$

$\square\ (\square\ \square_+\quad \square_-)$

(where $\square_+$ and $\square_-$ mean increasing and decreasing intervals with same direction respectively)

=> $\square \boldsymbol{M_e} = \{5;\ {}_5\square_{(+\text{ or }\square)}(G_i) = G_j\}$.

Let transformed object groups be:

G_1, G_2, G_3, G_4, G_5.

Then, visual movement from transformed shapes, $\boldsymbol{M_t}$, is discovered by satisfying the following rule:

R10: $\square_1(G_1) = G_2, \square_2(G_2) = G_3, \square_3(G_3) = G_4, \square_4(G_4) = G_5$

$\square\ (\square\ n\square_{(i+\text{ or }i\square)\text{ or }(s+\text{ or }s\square)})$

(where $\square_{(i+\text{ or }i\square)}$ and $\square_{(s+\text{ or }s\square)}$ means increasing or decreasing intervals, or increasing or decreasing scales in the same direction in transformed object groups)

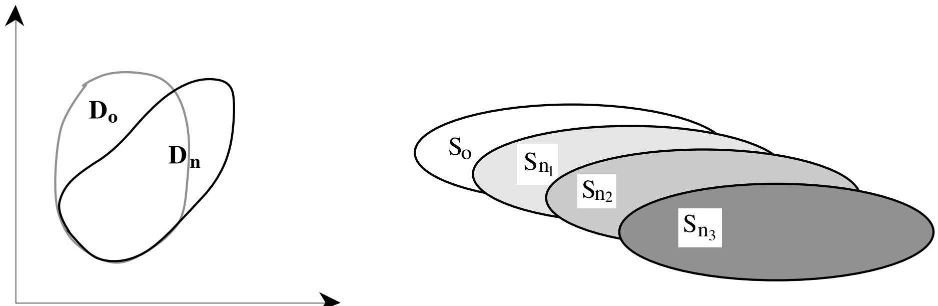
=> $\square \boldsymbol{M_t} = \{5;\ {}_5\square_{(i+\text{ or }i\square)\text{ or }(s+\text{ or }s\square)}(G_i) = G_j\}$.

As a result, visual symmetry, visual rhythm and visual movement are discovered if the above rules are satisfied.

5 The Use of Visual Semantic Emergence in Creative Designing

There are two classes of change possible in a state space view of design: addition and substitution (Gero, 1992). The concept of addition is that variables are added to the existing stock of variables which are used to describe the problem. On the other hand, the concept of substitution is that some existing variables are deleted and others added to produce a different set of possible designs. Creative designing can be represented in this state space view by a change in the state space. Process models for modifying a design space can be explained through additive or a substitutive processes.

The processes of visual semantics emergence are considered as important processes in the substitution of schemas. Figure 21 shows the notion of substitutive state space view and substitutive schemas. For example, an original or existing schema for shapes (S_o) is defined by the existing representation and existing variables. New schemas which have new representations and new variables are substituted. According to the relationships with various types of shape semantics, S_{n_1} could be a new schema for shapes and S_{n_2} and S_{n_3} could be new schemas for shape semantics, such as schemas for visual rhythm and for visual symmetry.



(b)

(a)

Figure 21: (a) The substitutive state space view of design: D_O is original state space of design and D_n is a new state space; (b) substitutive schemas where new schemas contain only a part of previous one (from Gero, 1992).

Using the emergent shape semantics for creative designing is an important potential of this work. In this section we describes how designers may be able to use the emerged shape semantics in their designing. The ideas are described through examples.

Figure 22(a) shows two reflectional symmetries discovered from the four L-shaped polygons which were drawn by the designer. Operations on objects, such as moving, reshaping or rotating, give opportunities for new designs to designers. If designers want to keep an emergent shape semantics, both reflectional symmetries in this example, the shape semantics is constrained to exist independent of other operations. The bold dotted reflectional axes in Figure 22(b) represents the axes adapted for designing. As a result, when one L-shape is moved by the designer, the reflected structures are automatically moved to maintain the reflectional symmetries in the system. Figure 22(b) illustrates a new possible design .

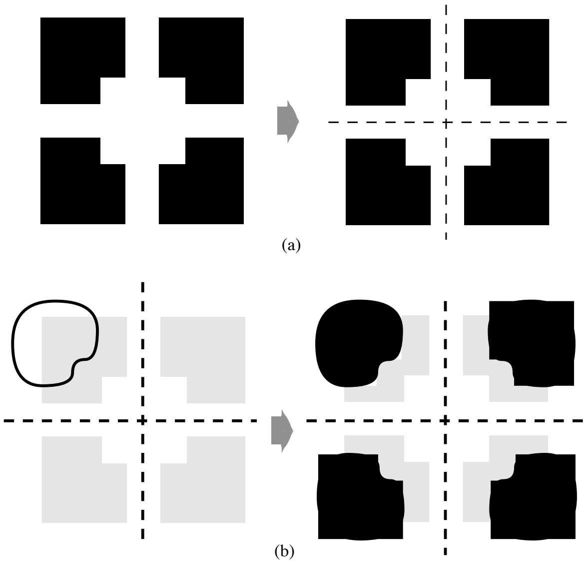


Figure 22: Use of emergent visual symmetry in design: (a) emerging reflectional symmetries; and (b) generating new reflectional symmetry by moving one part of (a) after choosing to maintain the emergent reflectional symmetries.

Figure 23(a) shows the primary shape as drawn by the designer. This shape has potentially a number of emergent semantics, one of which is visual rhythm. The representation of the emergent visual rhythm in Figure 23(a) is:

Unit =  ,
Group of units: G = (4↘, 3↗),
Representation of visual rhythm: ***R*** = 3{G(→)}.

The designer may now choose to make use of this new interpretation of what was drawn in a number of different ways. The visual rhythm can be maintained by reshaping the unit of group as shown in Figure 23(b). Therefore, the representation of this new visual rhythm is changed based on reshaping the unit. The representation of this new visual rhythm in Figure 23(b) is:

Unit = ,
Group of units: G = (4↘, 3↗),
Representation of visual rhythm: ***R*** = 3{G(→)}.

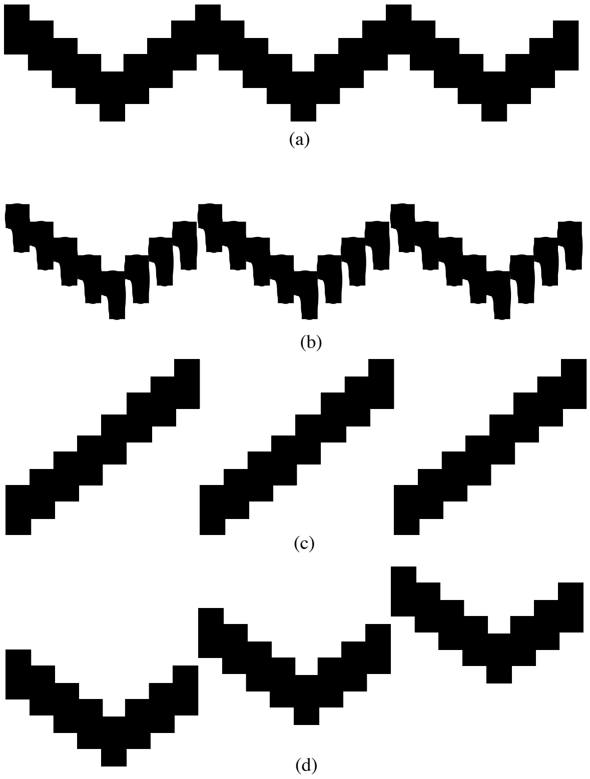


Figure 23: Use of emergent visual rhythm in design: (a) discovered visual rhythm; (b) generating new visual rhythm by reshaping unit of rhythm; (c) generating new visual rhythm by changing topological constraint on group; and (d) generating new visual rhythm by changing topological constraint on relationship between group.

Other types of visual rhythms are generated by changing the topological constraints (←, →, ↑, ↓, ↖, ↗, ↙ and ↘) on the emerged visual rhythm. For example, changing the topological constraints on the group is considered. Figure 23(c) shows a new visual rhythm obtained by changing the existing G = (4↘, 3↗), into G = (4↗, 3↗). The representation of this new visual rhythm is:

Unit = ■,
Group of units: G = (4↗, 3↗) = (7↗).
Representation of visual rhythm: ***R*** = 3{G(→)}.

Consider the situation of changing the topological constraints on the relationship between adjacent groups. Figure 23(d) shows a new visual rhythm produced by changing the topological constraints on relationship between adjacent groups, such as changing ***R*** = 3{G(→)} into ***R*** = 3{G(↗)}. The representation of this new visual rhythm in Figure 23(d) is:

Unit = ■ ,
Group of units: G = (4$\searrow$, 3$\nearrow$),
Representation of visual rhythm: $\boldsymbol{R}$ = 3{G($\nearrow$)}.

6 Discussion

This paper has presented an approach to the emergence of visual semantics, particularly from architectural design drawings. The effect of such an emergence in terms of creative designing is to introduce a new schema into the design and as a consequence to modify the state space of designs. As such this process of emergence becomes a creative designing process. Formal descriptions of various visual semantics processes have been given.

Visual semantics emergence produces both design potential and problems if it is to be utilised in designing. The problems primarily focus on the difficulty generated when so many semantics are emerged from a given description that it is not feasible for the designer to examine and evaluate them. This is a likely scenario if no control is placed on the number of possible semantics. The use of various heuristic controllers to limit the number of emergences is both feasible and simple to implement. For example, the first instance of a particular class of visual semantic emergence could be presented to the designer with a query as to whether that class of result was worth pursuing further. An example of a class visual semantic emergence may be sufficient to inform the designer.

As presented in Section 5 the potential of visual semantics emergence is to allow the designer to change focus and to move in another direction to the one currently being followed. The use of constraints provides a ready means to enforce the semantics as the design develops further. Visual semantics emergence is a computational process which provides the opportunity for the designer to be more creative.

Acknowledgments

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